Appendix B

Carbon Coefficients Used in This Report

Overview

The first edition of *Emissions of Greenhouse Gases in the United States*, published in September 1993, applied emissions coefficients for petroleum and natural gas developed by Marland and Pippin[1] and adopted by the Intergovernmental Panel on Climate Change.[2] Those coefficients, developed for broad international use, covered only the six petroleum product categories in the International Energy Agency's taxonomy. The Energy Information Administration (EIA) collects data on more than 20 petroleum products, and U.S. petroleum products often differ in composition from those consumed abroad. In the first edition of this report, EIA estimated emissions coefficients for the remaining petroleum products based on their underlying chemical composition. EIA also used emissions coefficients for coal by rank (anthracite, bituminous, subbituminous, and lignite) and State of production, developed using 5,426 coal samples from the EIA coal analysis file.

In 1994, EIA developed specific and updated emissions coefficients for all petroleum products in their data collection system, based on their density, heat content, and carbon share. These variables were estimated on the basis of the underlying chemical composition of the fuels and, where available, ultimate analyses of product samples.[3] An emissions coefficient for natural gas was also generated, based on 6,743 gas samples in a Gas Research Institute database. The magnitude of potential variation in emissions coefficients for fossil fuels is constrained by the limits imposed by the chemical properties of the hydrocarbon compounds that define the fuels.[4] In all but a few cases, the revised emissions coefficients differed from those developed by Marland and Pippin by less than 5 percent.

The composition of marketed petroleum products varies over time because of changes in exploration, recovery, and refining technology, economic changes (e.g., changes in the price of oil), and regulatory changes (e.g., requirements for reformulated gasoline in the Clean Air Act Amendments of 1990). Because motor gasoline consumption is a major contributor to U.S. greenhouse gas emissions and has experience important changes in composition over the last decade, EIA provides annual updates of the its emission coefficient (Table B1).

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[1]G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, Vol. 14 (1990), pp. 319-336.

[2]Intergovernmental Panel on Climate Change, *Estimation of Greenhouse Gas Emissions and Sinks* (Paris, France, 1991), p. 2-18.

[3]An ultimate analysis provides an exact breakdown of the elements present in a compound or mixture.

[4]For a more detailed discussion of fossil fuel chemistry and emissions coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92, web site www.eia.doe.gov/oiaf/1605/87-92rpt/appa.html.

Table B1. Full Combustion Carbon Coefficients

(Million Metric Tons of Carbon per Quadrillion Btu)

Fuel	1990	1991	1992	1993	1994	1995	1996	1997	1998	P1999
Petroleum										
Motor Gasoline	19.41	19.41	19.42	19.43	19.45	19.38	19.36	19.35	19.36	19.36
LPG	16.99	16.98	16.99	16.97	17.01	17.00	16.99	16.99	16.99	16.99
Jet Fuel	19.40	19.40	19.39	19.37	19.35	19.34	19.33	19.33	19.33	19.33
Distillate Fuel	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Residual Fuel (All Other)	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Residual Fuel (Utility)	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29	21.29
Asphalt & Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Petrochem Feed	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Aviation Gas	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Waxes & Misc.	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Other:	17.46	17.83	17.39	16.12	16.36	15.69	16.27	16.57	15.59	14.84
Coal Residential & Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00
Coal Indus. Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56
Coal Indus. Other	25.58	25.60	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63
Coal Electric Utility	25.68	25.69	25.69	25.71	25.72	25.74	25.74	25.76	25.76	25.76
Flare Gas	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92	14.92
Natural Gas	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47	14.47
Crude Oil	20.16	20.18	20.22	20.22	20.21	20.23	20.25	20.24	20.24	20.19

P=preliminary data.
Source: Energy Information Administration, Emissions of Greenhouse Gases in the United States 1998, DOE/EIA-0573(98) and estimates presented in this report.

The EIA also provides annual updates of of the emissions coefficient for crude oil. Crude oil consumption in the United States is a very small portion of carbon emissions, because nearly all crude is refined into finished petroleum products. However, crude oil refinery input can be used to develop a national mass balance estimate of carbon emissions that may be used as a benchmark for the more disaggregated estimation approach used by EIA. EIA has developed a regression equation reflecting the relationship between the density, sulfur content, and carbon content of crude oil. From these data a crude oil emissions coefficient can be calculated. This regression equation is applicable for any nation that collects these basic petroleum statistics and supports a mass balance approach to estimating emissions where detailed product data are not collected.

In 1997, EIA began publishing separate emissions coefficients for LPG fuel use and LPG nonfuel use. LPG may be used as fuel or as a petrochemical feedstock. About three quarters of the carbon in petrochemical feedstocks will be sequestered. Further, if the mix of paraffinic hydrocarbons used for petrochemical feedstock differs substantially from those used for fuel, using a single emissions coefficient for LPG will bias estimates of emissions. Thus, EIA now annually adjusts the emissions coefficient for LPG based on the mix of compounds used as fuel and feedstock.

Finally, the EIA provides annualized emissions coefficients for jet fuel consumed during the period 1990 through 1996. During that period jet fuel consumed in the United States underwent a dramatic change in composition. Until 1993, two types of jet fuel were widely used in the United States. Kerosene-based jet fuel was generally used in the commercial airline industry and naphtha-based jet fuels were used primarily by the U.S. Department of Defense. The emissions coefficient for naphtha-based jet fuels was about 3 percent higher than that for kerosene-based jet fuel. In 1989, 13 percent of all jet fuel consumed was naphtha-based. By 1996, that figure had fallen to 0.3 percent, and in 1997 total naphtha-based jet fuel consumption was negligible. Thus, the emissions coefficient for jet fuel, weighted by consumption of each fuel type, fell steadily between 1988 and 1996 and has now stabilized at the level of kerosene-based jet fuel. Notably, the emissions coefficient for jet fuel is now the same as the coefficient for motor gasoline.

This appendix discusses the updated 1999 emissions coefficients for motor gasoline, crude oil, and liquified petroleum gases. Because the emissions coefficient for jet fuel is now static it will not be examined further here.[5]

Motor Gasoline

Motor gasoline consumption accounts for about 20 percent of all U.S. greenhouse gas emissions. Thus, changes in composition can have important effects on national emission levels. As with all petroleum products, the emissions coefficient for motor gasoline is a function of its density and carbon content. This relationship is particularly clear in the case of motor gasoline because the share of impurities found in the fuel must be kept very low to maintain the operating condition of modern automobile engines and limit the environmental effects of vehicle use. Motor gasoline density varies between summer and winter grades and from low octane to high octane. This variation takes into account the differing performance requirements of gasoline associated with temperature changes. Partly as a result of the leaded gasoline phaseout, the density of gasoline increased slowly and steadily across all octane grades and in all seasons from 1987 through 1994.[6] In order to maintain the "anti-knock" quality and octane ratings of motor gasoline in the absence of lead, the portion of aromatic hydrocarbons used in gasoline was increased. Aromatic hydrocarbons take the form of C_nH_{2n-2}, a lower ratio of hydrogen to carbon than other hydrocarbons typically found in gasoline. Because carbon is much heavier than hydrogen, this lower ratio results in increased fuel density and higher shares of carbon. As a result, the emissions coefficient for motor gasoline rose slowly from 19.39 million metric tons carbon per quadrillion Btu in 1988 to 19.45 million metric tons carbon per quadrillion Btu in 1994. Table B2 shows the increasing densities and emissions coefficients between 1990 and 1994.

Table B2. Changes in Motor Gasoline Density, 1990-1999

Fuel Grade	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Winter Grade										
Low Octane	62	61.8	61.4	61	60.1	59.8	60.6	61.5	61.8	61.6
Mid Octane	60.8	60.4	60.2	59.9	59.4	59.1	59.9	60.7	61.2	61.3
High Octane	59	59.3	59	58.7	58.5	58	58.5	59.3	60	60.3
Summer Grade										
Low Octane	58.2	58	57.4	56.1	55.7	56.1	56.9	57.1	57.6	57.7
Mid Octane	57.4	57.1	56.4	55.5	54.8	55.6	56.2	56.6	56.7	57.4
High Octane	55.5	55.7	55.6	54.4	53.8	55.1	55.3	56.4	55.7	57.4
Average Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**19.41**	**19.41**	**19.42**	**19.43**	**19.45**	**19.38**	**19.36**	**19.35**	**19.36**	**19.36**

[a]Emissions coefficient weighted for reformulated gasoline, which has a lower density than standard gasoline.
P = preliminary data.
Sources: National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* and *Motor Gasoline, Winter* (1990-1999); and M. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Vol. 2, Appendices A-S (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6. Properties of reformulated fuels from California Air Resources Board.

In 1995, a requirement for reformulated gasoline in nonattainment areas implemented under the Clean Air Act Amendments changed the composition of gasoline consumed in the United States. In reformulated gasoline, methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether (TAME) are added to standard gasoline to boost the oxygen atoms in the gasoline mixture. The increased number of oxygen atoms reduce the emissions of carbon monoxide and unburnt hydrocarbons. This also results in a reduced carbon share in these molecules.In contrast to an average carbon share of 86.6 percent for standard motor gasoline, MTBE is 68.2 percent carbon and TAME is 70.2 percent carbon. (Table B3) The average gallon of reformulated gasoline includes about eight percent MTBE and 1 percent TAME. Thus, in 1995 the overall emissions coefficient for gasoline fell to 19.38 million metric tons per quadrillion Btu. About 20 percent

[5]For a more detailed discussion of jet fuel coefficients, see Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), Appendix A, pp. 73-92; and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1997*, DOE/EIA-0573(97) (Washington, DC, October 1998), Appendix B, pp. 105-110.

[6]National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer*, and *Motor Gasoline, Winter* (1984-1994).

of all gasoline consumed in 1998 and 1999 was reformulated, leading to a consumption-weighted emission coefficient of 19.36 million metric tons per quadrillion Btu for both years.

Table B3. Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)	Emissions Factor (Million Metric Tons Per Quadrillion Btu)
MTBE	59.1	68.2	16.92
ETBE	59.1	70.5	17.07
TAME	52.8	70.5	17

Sources: California Air Resources Board and estimates developed for this report.

To derive an overall emissions coefficient for gasoline, individual coefficients for standard motor gasoline consumed in the winter and summer months, respectively, were developed. These coefficients were based on the densities of product samples collected by the National Institute on Petroleum and Energy Research used in conjunction with a carbon share of 86.6 percent as estimated by Mark DeLuchi.[7] Emissions coefficients for reformulated fuels consumed during the summer and winter were calculated using the following procedure. First, the carbon share of each additive used in reformulated gasoline was calculated from its chemical formula and combined with the additive's density and energy content as provided by the California Air Resources Board to produce individual coefficients for each fuel additive. Next, the reformulated fuel was separated into its standard fuel components and its additive portions based on fuel samples examined by NIPER.[8] The additive portions were defined as the net increase in MTBE, ETBE, or TAME as compared with the additives in standard fuel, since small amounts of these compounds are present in standard gasoline. The emissions coefficients for standard gasoline and for each of the additives were then weighted by their proportion in reformulated fuel to arrive at a coefficient for reformulated fuel in each season.

After independent coefficients were developed for both standard and reformulated fuel, each season's coefficients were combined by weighting according to the ratio of standard vs. reformulated consumption. The combined summer and winter coefficients were then weighted based on seasonal consumption, with just over half occurring in summer, to derive an overall emissions coefficient for motor gasoline.

Crude Oil

While crude oil composition is highly heterogeneous, the share of carbon in a fixed amount of crude oil (e.g., a gallon or barrel) varies somewhat systematically with such commonly available identifying characteristics as density and sulfur content. Because the economic value of a barrel of crude oil is largely a product of the oil's density and sulfur content these values are regularly recorded. Further, EIA maintains detailed data on the average density and sulfur content of crude oil entering U.S. refineries.[9] Thus, the annual emissions coefficient for crude oil is pegged to these two variables.

Ultimate analyses of 182 crude oil samples were used to derive a relationship between crude oil density, sulfur content, and the percentage of carbon in crude oil. The sulfur content and density of these samples was regressed against their carbon content. This regression analysis produced the following equation, which is used to estimate the carbon content of crude oil:

$$\text{Percent Carbon} = 76.99 + (10.19 * \text{Specific Gravity}) + (-0.76 * \text{Sulfur Content}) .$$

[7]National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer*, and *Motor Gasoline, Winter* (1980-2000); and M. DeLuchi, *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*, ANL/ESD/TM-22, Vol. 2, Appendixes A-S (Chicago, IL: Argonne National Laboratory, November 1993), p. c-6.

[8]National Institute of Petroleum and Energy Research, *Motor Gasoline, Summer* (1995-1999), and *Motor Gasoline, Winter* (1994-1995 to 1999-2000).

[9]Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years).

Annualized emissions coefficients are developed by inserting the average density and sulfur content for crude oil entering U.S. refineries for each year from 1987 through 1999. This provides the share of carbon in an average barrel of oil during each year. After the share of carbon is derived, it is used in conjunction with fuel density to estimate the total mass of carbon in a barrel of crude oil. An emissions coefficient per unit of energy is then calculated using EIA's standard energy content for crude oil of 5.8 million Btu per barrel.

The 1999 emissions coefficient for crude oil is 20.19 million metric tons carbon per quadrillion Btu, down from the 1998 value of 20.24 million metric tons per quadrillion Btu. The density of crude oil entering U.S. refineries declined, while the sulfur content continued to climb (Table B4).

Table B4. U.S. Crude Oil Characteristics, 1990-1999

Characteristic	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Density (API Gravity)	31.86	31.64	31.32	31.30	31.39	31.30	31.13	31.07	30.98	31.31
Density (Specific Gravity)	0.8662	0.8674	0.8691	0.8692	0.8687	0.8692	0.8701	0.8704	0.8709	0.8691
Sulfur Content (Percent)	1.1	1.13	1.16	1.15	1.14	1.13	1.15	1.25	1.31	1.33
Carbon Share (Percent)	84.98%	84.97%	84.96%	84.97%	84.98%	84.99%	84.98%	84.91%	84.87%	84.84%
Emissions Coefficient (Million Metric Tons Carbon per Quadrillion Btu)	**20.16**	**20.18**	**20.22**	**20.22**	**20.21**	**20.23**	**20.25**	**20.24**	**20.24**	**20.19**

Note: Emissions coefficients assume 100 percent combustion.
Sources: Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years); and Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), p. 91.

Liquefied Petroleum Gases

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and *n*-butane. Because each of these hydrocarbons is a pure paraffinic compound, their carbon shares are easily derived by taking into account the atomic weight of carbon (12) and the atomic weight of hydrogen (1). Thus, for example, the carbon share of ethane, C_2H_6, which has an atomic weight of 30, is 80 percent. The densities of these compounds are also well known, allowing emissions coefficients to be calculated easily. EIA collects data on consumption of each compound and then reports them as LPG in the *Petroleum Supply Annual*.[10] By weighting each compound's individual emissions coefficient by its share of energy consumed, an overall emissions coefficient for LPG is derived.

More than 95 percent of all ethane and just under 85 percent of butane consumed goes to nonfuel uses. In contrast, nearly all LPG used as fuel is propane. Thus, the emissions coefficient for LPG used as fuel is 17.20 million metric tons carbon per quadrillion Btu, which is the emissions coefficient for propane (Table B5). On the other hand, the carbon emissions coefficient for LPG for nonfuel use is pulled down to 16.88 million metric tons carbon per quadrillion Btu by the large presence of the lighter ethane and its emissions factor of 16.25 million metric tons per quadrillion Btu.

[10]Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (Washington, DC, various years), Table 2.